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A Review of the Fundamental Elements and Key Parameters in Trombe Wall System Design

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ABSTRACT

Trombe wall technology is a passive solar system that integrates solar energy into building design to enhance cooling, heating, and natural ventilation. This research reviews and compares different types of Trombe walls based on their materials, advantages, and disadvantages. It also examines the key parameters that influence their design and performance. The parameters include wall form, height, material, glass layer specifications, area, storage wall thickness, color, air gap depth, thermal insulation, shading devices, and ventilation openings. The importance of adjusting these parameters is analyzed to enhance building energy efficiency, indoor air quality, and occupant comfort. Moreover, the general optimal values of these parameters are proposed based on previous studies, along with context-specific values determined by climatic conditions. The findings showed Trombe walls to be a possible design method for sustainable buildings, mainly in places where very high temperature differences exist during the daytime. Also, the optimal ranges given can be used as a very practical guide for designers and engineers in setting up adequate Trombe wall systems in given climatic situations.

1. INTRODUCTION

Designed in 1967 by Félix Trombe, the Trombe wall (TW) technology has become a means of ensuring natural ventilation and light. It greatly improves environmental conditions and air quality; therefore, energy use relative to air conditioning systems is lessened [1, 2]. Accordingly, TWs are an essential part of the passive solar strategy that is implemented in different climates to aid in the sustainability of the building because of their simplicity [3]. This technology integrates passive solar energy systems with the building design, taking into account the relationships between humans and the environment. It is an eco-friendly treatment for exterior walls, providing natural lighting and ventilation. Furthermore, TWs can be implemented in various climates, particularly in regions experiencing significant temperature differences between day and night [4-6]. Natural ventilation, when generated by the building structure itself, is considered unstable, as it is influenced by the limitations of natural conditions [7, 8]. However, it is possible to enhance ventilation performance when solar energy is used to regulate airflow and support natural aeration. The effective combination of natural ventilation and solar energy results in a sustainable system. Architect Hassan Fathy emphasized the impact of solar energy on airflow, stating that "the availability of certain conditions enables the architect to make good designs in which he can use the sun as a driving force that achieves continuous movement of air." [9]. Appropriate natural ventilation, particularly in summer, prevents the transfer of accumulated heat from the walls to the interior, thereby keeping the building as cool as possible [10]. This method has become one of the most effective technologies in buoyancy-driven natural ventilation, and serves as a key architectural element in green building design, promoting efficient natural ventilation and heating [11, 12].

2. A BRIEF HISTORY OF TW

Humans have long used the concept of stout walls made of mud or pebbles to capture solar energy during the day, and release it slowly and evenly to warm buildings at night [13, 14]. This principle has been applied in modern architecture through the integration of TW. These structures, also known as solar heating walls, thermal walls, mass walls, collector storage walls, or solar energy-saving walls [15, 16], function as an important element of sustainable architecture. Their use includes natural ventilation as part of passive cooling or heating systems in buildings [17, 18]. By reducing environmental degradation, lowering carbon emissions—a major contributor to global warming- and addressing challenges related to energy sustainability and pollution, these technologies contribute significantly to environmental preservation [15]. The foundational principle of this wall design was initially proposed by Edward Morse in 1881, and later refined by the French inventor Félix Trombe in 1967, after whom the structure is now named [19]. To this day, the TW remains an effective component of passive solar systems.

The idea behind its development is to utilize radiant energy for ventilation and heating, while also providing thermal comfort to building occupants under various climatic conditions. For these reasons, the TW is one of the most extensively studied elements for this application [1, 15, 20]. With the development and advancement of industries and technology, particularly in the field of electric power, air conditioning (AC) began to replace natural ventilation systems in the 1930s. The reliance on these systems further increased with continued advances in powered ventilation technologies. However, over the past thirty years, there has been a growing movement to promote awareness of green buildings and more sustainable living [15]. In the last two decades, interest in the TW has gradually increased alongside the global energy crisis [21] positioning it as a promising method for conserving energy and maintaining indoor air quality [22]. The literature and previous studies on the TW have varied, influenced by diverse research approaches, and ongoing developments in technology, measurement tools, and computer programs [23].

3. TW FUNCTIONS

Thick walls constructed from high thermal mass materials have been used for centuries to absorb and store heat from sunlight during the day, gradually releasing it at night. This traditional yet effective design remains applicable in modern construction and building renovations [14, 24]. A TW stands out as a very particular example of this concept-functioning both as a heavy thermal wall and as a solar chimney, accepting sunlight to create natural airflow by convection [25, 26]. As well as storing heat, TWs promote ventilation, provide insulation, and ensure consistent temperatures inside. Using solar energy to control indoor climates lowers reliance on mechanical cooling systems, which in turn provides for an overall lower energy demand [8, 27].

Such passive solar systems form the core of sustainable architecture, providing heat with natural air circulation at no energy cost [11, 12]. Their versatility makes them strong candidates for greater energy efficiency and indoor air quality [22]. Various strategies have been investigated by researchers to optimize TWs. For example, Jaber and Ajib [23] investigated the optimization of their designs in Mediterranean climates to reduce heating demand, whereas Alzaed [1] and Mokheimer et al. [28] looked at their efficacy for lowering cooling requirements in Middle East buildings. Further, Hamidi et al. [25] confirmed their role in promoting natural ventilation in different Moroccan climates, showing their adaptability.

4. TW TYPE

Recent studies have increasingly focused on the physical design of TWs, yielding promising results as the new versions have proven to be more efficacious than their older counterparts. Furthermore, the newer versions have been edited to cast a wider set of applications. The classic TW is shown in Figure 1 and later adapted to various weather conditions.

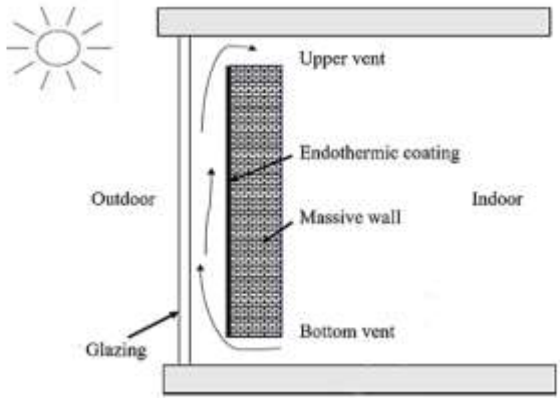


Figure 1. Standard TW [29]

To fabricate these walls, several materials can be used, primarily those with sufficient thermal storage capacity, including adobe, stones, concrete, and bricks. Air is supplied to the indoor space through two vents in the wall. Solar energy transmitted through the external glazing is absorbed and stored by the black wall. A portion of the absorbed heat is transferred into the indoor area by radiation and convection, while another portion is conducted through the vents by air circulation resulting from the buoyancy effect.

The developed TWs, shown in Figure 2, are designed to enhance thermal performance and improve their adaptability to various environmental conditions. The available types of TWs are [15, 30]:

1. Classical TW: Contains a black thick wall (made of materials like stone, brick, adobe, or concrete), external glazing, and a ventilated air gap.
2. Composite TW (Trombe-Michel Wall): An insulating wall is added at the back of the thick wall to diminish heat loss.
3. Zigzag TW: Comprises three sections constituting a V shape, designed to relieve extreme glare and heat gain.
4. Water TW: A wall-shaped water container is used instead of material for heat storage.
5. Solar Trans wall: It is a transparent sectional water wall that permits external visibility and delivers thermal storage.
6. Fluidized TW: The gap between the glass cover and the TW is loaded with low-density, highly absorbing particles.
7. Photovoltaic (PV) TW: Integrates solar cells into the classic TW.
8. TW with Phase Change Materials (PCMs): The PCMs are used to store latent heat, demanding less space, and being lighter in weight compared to mass walls.
9. Thermochromic TW: The wall is coated with a thermochromic material that changes transparency based on temperature.

A comparison between various types of TW is introduced in Table 1, showing their materials, advantages, and disadvantages [16, 30-32].

It can be concluded from Table 1 that the best thermal performance is provided by the water TW and the PCM-enhanced TW, although both require more maintenance. The PCM-enhanced TW and PV TW involve higher costs, but they offer greater efficiency, whereas the classical TW remains the most cost-effective option. The PCM, PV, zigzag, and fluidized walls represent advanced optimization strategies, despite their degree of complexity.

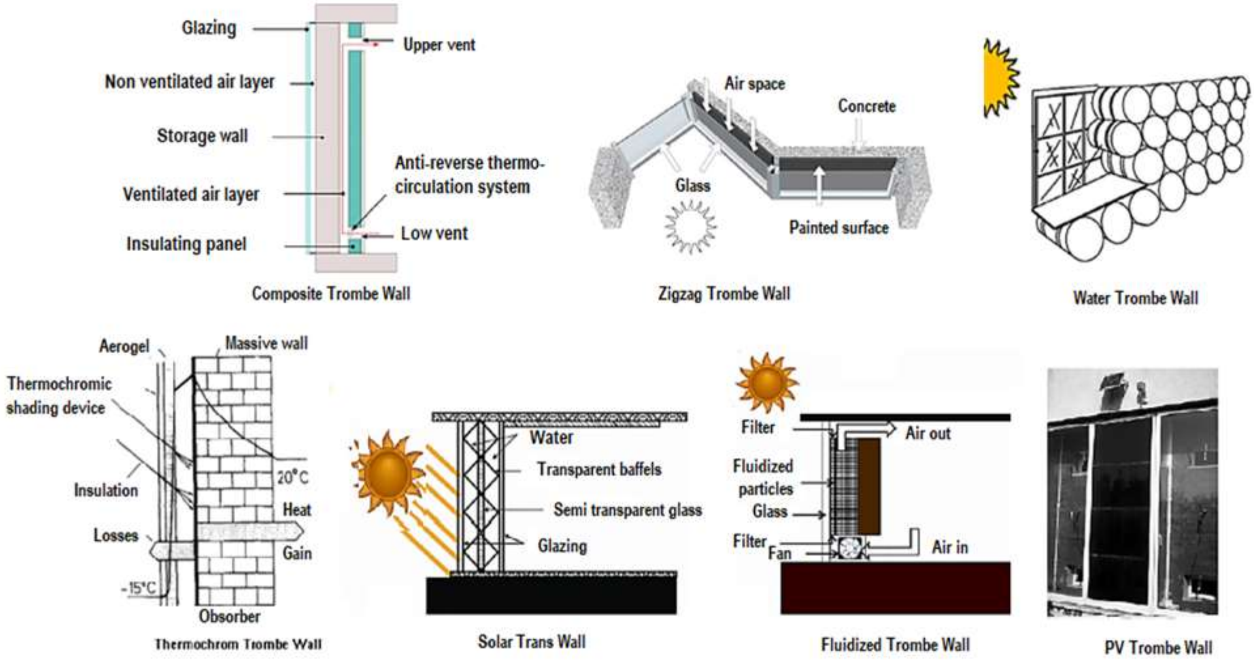


Figure 2. Trombe wall types [30]

Table 1. Comparison of TW types

No.	Type	Materials	Advantages	Disadvantages
1	Classical TW	Made of stone, brick, adobe, or concrete	-Simple and economical design -Reliable operation -Effective for passive solar heating	-Can increase the building's dead load -Potential for reverse heat transfer during the night
2	Composite TW	Similar to classical, but insulation is added	-Reduces heat loss from inside to outside -Improved thermal efficiency	-More complex construction -Higher initial cost
3	Zigzag TW	Similar to classical but with a unique shape	-Reduces glare and excessive heat gain -Suitable for sunny climates	-More complex design and construction require more space
4	Water TW	Water containers, made of glass or plastic	-High heat storage capacity -Transparent, allowing for natural light	-Potential for leaks -Requires maintenance to prevent algae growth
5	Solar Trans wall	Parallel glass walls with a partially absorbing plate	-Allows for natural light and exterior views- Effective thermal storage	-Complex construction. -Higher cost
6	Fluidized TW	Particles such as sand or other granular materials	-Enhanced heat absorption -Improved thermal performance	-Potential for particle movement and settling -Requires careful design to prevent clogging
7	Photovoltaic (PV) TW	PV panels, typically silicon-based	-Dual functionality (generates electricity in addition to providing thermal storage)	-Higher initial cost -Requires maintenance of PV panels
8	PCM-Enhanced TW	PCMs such as paraffins, fatty acids, or hydrated salts	-Higher heat storage capacity per unit mass -Reduces indoor temperature fluctuations -Lighter in weight compared to mass walls	-Requires careful selection of PCM type and quantity -Potential issues with PCM encapsulation and thermal control

5. TW DESIGN PARAMETERS

For an effective TW design, the following aspects must be considered, emphasized, and optimized to improve its performance and functionality.

5.1 TW structure

During the day, the TW structure functions as a solar air collector, absorbing and storing solar heat to be released in the evening. This structure includes several basic elements, which will be discussed in detail in the following paragraphs, along with the key parameters affecting its operational efficiency. The layout method of the system also significantly influences its performance and configuration options. These parameters include shape, height, and area.

5.1.1 TW shape

Another major factor affecting the performance of TWs is the shape of the wall. Several studies have been conducted on the different shapes of the walls and how they affect the overall efficiency of the system.

Aliwi and Kamoo [27] stated that one type of TW, known as Zigzag-TW, contained three main parts-two of these parts form a V-shaped fence, and the third one is the classic TW. Such a TW reduces very high glare and heat gain on sunny days. Rabani et al. [33] proposed a novel TW design to receive solar radiation from three sides (east, west, and south).

According to the study, the new design can receive about 16% more solar radiation in winter than the conventional TW.

Based on the study carried out by Farrugia [34], the investigation carried out sought to identify how the shape of a TW influences its thermal performance, particularly when working with translucent PCMs. The study looked at modeling and simulation methods to analyze the thermal behavior of various TW geometries in two climates: hot-dry and temperate. A phase approach was adopted where essentially a flat wall was changed on two scales by several design strategies. From these simulation results, the thesis offered design recommendations for geometrically optimized TWs with PCMs for office buildings suited to different climates.

Omara and Abuelnuor [30] indicated that modifications and research on the typical TW have led to the emergence of several types with different forms and characteristics, including Zigzag TWs, composite TWs, solar Transwall water TWs, Photovoltaic (PV) TWs, PCM-enhanced TWs, and fluidized TWs. A comparison of these types is presented in Section 4.

5.1.2 TW height

Many studies have highlighted the impact of TW height. Gan [35] explained that the height of the storage wall affects the buoyant force, and, consequently, the airflow rate. The experiment demonstrated that the flow rate for a 3 m-high TW with a heat gain of 125.4 watts per square meter is equivalent to that of a 2.4 m-high wall with a heat gain of 219 watts per square meter, corresponding to a heat flow rate of Q = 39.81 seconds per square meter. An increase in TW height by one-quarter is comparable to a three-quarter increase in wall heat gain. However, the height of the TW is typically limited by the height of the building. This contrasts with the solar chimney, which offers more flexibility in system design, allowing height adjustments to optimize the stack effect. The same applies to the experiment conducted by Li et al. [8] to analyze the impact of TW height on airflow velocity using mathematical modeling and simulation using ANSYS Fluent. Based on the results, the higher the wall, the higher the airflow velocity inside the wall. This enhances the wall's ability to improve building ventilation in different climates.

Shashikant and Naik [36] stated that the height and thickness of the TW affect the ventilation rate generated by the buoyancy effect. Consequently, the ventilated TW was installed at the maximum height allowed on the space wall. However, the study did not examine the effect of height, focusing instead on the location of openings, and their impact on airflow in a TW with a 20 cm wall thickness, a 15 cm air gap, and a height of 2.69 m, equal to the height of the living space.

For the semi-arid climatic conditions, Dhahri et al. [22] tested the efficiency of a TW with an outer glass, with specifications of a 30 cm-thick wall 2.4 m in height, and a 30 cm air gap. The simulation results showed that the TW maintained indoor temperatures around 20°C in winter. However, it caused overheating in summer, despite reducing indoor temperatures by 6.1°C. The findings indicated that while TWs improve winter thermal comfort, modifications are needed to prevent overheating and enhance summer performance.

In a follow-up study, Dhahri et al. [37] assessed the performance of various TW designs and roof geometries to improve heating in buildings, particularly in high-humidity, low-temperature climates. They examined a TW with a 0.30-meter-thick wall, a height of 2.4 meters, and a 0.3-meter air gap. The results revealed that this configuration could provide satisfactory thermal performance when paired with a butterfly roof.

Kalair et al. [38] performed an investigation into the energy efficiency and thermal comfort of a TW-equipped multi-energy building with a 4 m TW in the semitropical oceanic climate of Melbourne, Australia. They have concluded that the wall was acting to store heated air at 40°C during winter, and at 55°C during summer.

5.1.3 TW area

Many researchers have shown how important the percentage of TW area over the total wall area is for analyzing TW performance. Jaber and Ajib [23] studied the significance of this ratio in relation to residential buildings of Mediterranean countries in environmental, thermal, and economic perspectives. The installed test TW was 3 m tall, 20 cm thick, with an air gap of 15 cm, and a single layer of glazing. The results showed that the optimal TW area ratio was 37%. Moosavi et al. [14] studied the situation of a bedroom in Yazd CT in a hot-dry climate. It was found that the application of a TW for two-thirds of the wall area was most effective since it greatly reduced heating load by 86%. In 2018, Bogdanovic et al. revealed that the unventilated TW with the most effect covered 75% of the wall area. The research was conducted in Serbia for a 100 m² space. Four specific designs of the southern wall, ranging from 0%, 25%, 50%, 75%, and 100% areas, have been tested for the TW area, posing a 30 m² southern wall of 2 cm air gap and a 20-cm-thick storage wall. The results demonstrated that such a configuration significantly reduces the heat required to warm the building [4]. Samiev et al. [2] analyzed the TW's ability to reduce energy consumption and heat emissions in a standard three-room residential building in Uzbekistan. Depending on the thermal insulation level, the optimal TW area ranged from 24.9% to 66.4% of the building façade, with the study concluding that increasing the TW area is more effective than improving insulation alone.

5.2 The storage wall

The wall component in a TW is made of solid material to absorb and store solar energy. Its function relies on many features:

5.2.1 Storage Wall Thickness

An essential factor in the effectiveness of TWs is the thickness of the massive wall [39]. The massive wall or the storage wall retains heat and prevents thermal energy from escaping the interior space [40]. The wall's efficiency is directly related to the thickness of the storage component, which often influences both heat loss and adaptation to weather conditions [27]. The thickness must be properly balanced: reducing it may cause significant temperature fluctuations inside the building, while increasing it may limit internal heat exchange [39].

Several studies have examined the impact of wall thickness and reported varying results. One study found that a thickness of approximately 40 cm can be ideal for heat storage [41]. Nevertheless, other studies indicated that in dry climates, using bricks with a 40 cm thickness and two air gaps (5 cm and 10 cm wide) can produce highly favorable outcomes [42, 43].

5.2.2 Storage wall weight and size

Generally, heat accumulation in the wall is directly influenced by the increase in the bulk of TWs; however, this also adds to the weight of all permanent building elements. Therefore, researchers have worked extensively to address this issue through the use of insulation, which can reduce the required size of the storage wall [41]. Several studies have examined the use of phase-change materials (PCMs) for thermal storage. These materials can store energy in relatively small volumes, as they are lighter than conventional materials. In this context, multiple researchers have conducted studies—for example, Zalewski et al. [44] showed that PCMs transfer energy to indoor space more quickly than concrete walls due to their superior energy storage capability. Elsaid et al. [16] indicated that insulation can reduce the size of the mass wall and improve efficiency by up to 56%. Furthermore, using PCMs is recommended because they offer high storage capacity in a compact form, resulting in a reduction in the overall size and weight of the storage wall.

5.2.3 Storage wall material

Selecting the appropriate material for the storage wall is crucial to the effectiveness of the TW system. Bogdanović et al. [4] discussed the potential use of any material with high thermal capacity in TWs. Limestone, solid brick, and concrete are the most common building materials due to their high thermal storage capacity, low energy consumption, and affordability. In massive walls, these materials are sometimes combined with others, such as phase change materials, photovoltaic cells, and thermal insulation, since the concept of the TW relies on a storage wall made of a material capable of absorbing significant heat. This material plays a key role in heat storage, and the processes of convection and conduction, which directly affect the wall's performance [4, 24, 45]. However, suitable materials for constructing a storage wall should also have both high storage capacity and low weight [15]. Özbalta and Kartal [46] investigated diverse materials for Trombe walls in Turkey, such as autoclaved aerated concrete, brick, and reinforced concrete, to examine heat gains. They found that reinforced concrete has the best thermal gains, which confirms the storage wall materials for heat transfer.

Similarly, Kamal and Mishra [47] compared various materials used in storage walls, including porous materials (marble and quartz) and non-porous materials (brick and concrete). Their findings revealed that the thermal efficiency of porous walls is higher than that of non-porous ones.

5.2.4 Storage wall colour

The coating materials on the external surface of the storage wall are among the key characteristics and influencing factors of TWs. Dark colours tend to absorb solar radiation more efficiently, thus increasing the heat storage capacity of the TW [13]. The heating wall's outer surface is usually painted black so that solar energy absorption is maximized; black, having an absorption factor of about 90–100%, is the best choice. White, on the other hand, has an absorption factor of just 20–30% [45]. Dabaieha and Elbably [48] suggested a ventilated TW for enhancing residential building performance under semi-arid climates. The design featured the storage wall painted light grey instead of black so that minimal solar radiation was absorbed, and temperature rise was kept at a minimum. Their experiments proved that the proposed TW, double-glazed with a 6 cm air gap, grey paint, a wool curtain inside the air gap, and an outside wooden curtain, improves TW performance, enhances thermal comfort, and reduces heating and cooling loads.

5.3 Air gap

This air gap is the space between the glazing and the thermal mass wall. This wall absorbs and retains solar radiation whilst allowing convective heat transfer. The air gap is of prominent importance for the thermal balance of the TW, because it is in the path of heat transfer and airflow. Optimizing its width, ventilation, and material properties enhances winter heating and summer cooling, thereby making it a more effective passive solar system. Faris et al. [45] investigated changes in air gap thickness (1, 2, 3, and 4 cm) in a TW with a constant storage wall thickness, assuming an air entry velocity of 2 m/sec, to compare the distribution of air velocity and temperature in the room. The study showed that air velocity in the gap depends on two factors: first, the temperature difference between hot and cold air, and second, the thickness of the gap, with an inverse relationship between gap thickness and air velocity. A smaller air gap increases the air velocity. Consequently, the study concluded that a 1 cm air gap is the most effective.

A study explored the relationship between air gap width, airflow rate, and heat effectiveness in torrid weather. It was found that heat effectiveness reached approximately 80% when the gap width was 0.3 m, with the best results recorded at a solar energy input of 100 watts/m² [49]. Another study examined different air gap widths within a 40 cm-thick Trombe storage wall in similarly hot conditions. The results showed that a 10 cm gap provided optimal air ventilation during the daytime [42]. A further study conducted in Latakia, Syria, investigated the effect of variable TW air gap thicknesses in both winter and summer. It concluded that the optimal gap was 4 cm between the insulation and the storage wall, and 2 cm between the wall and the glass [50]. One study aimed to improve system efficiency by testing various TW designs and techniques. It found that, for natural convection systems, the ideal air gap width between the storage wall and the glass layer ranges from 4 to 9 cm [15]. Moreover, another study, conducted in Yazd/Iran, characterized by torrid weather, reported that TW effectiveness declined when the air gap exceeded 10 cm [14]. In contrast, in the cool and wet winter climate of Kirkuk/Iraq, Abbas et al. [51] conducted a study to develop a computational model of a black concrete TW with a thickness of 10 cm. The study aimed to investigate the impact of air gap width on a fabricated wall equipped with two top, and two bottom slits. Various air gap widths were tested. The findings showed that power usage could be reduced, leading to a balance between internal and external temperatures and improved airflow. An analysis of heat exchange, airflow patterns, and airflow rate within the gap was carried out to enhance the TW's performance in ventilating a large space using ten different double-glazed TW designs in an environment with a temperature of 15°C. The results suggested that a wall with a thickness of 0.3 m and an air gap width between 5 and 8 cm provided a noticeable improvement in airflow compared to the other designs [52].

Another study investigated TW thermal performance in residential buildings located in Sohag, Egypt, a region characterized by torrid summer weather. The experiment tested three air gap depths between the wooden wall and the glass panel (10, 20, and 30 cm). The results indicated that a 30 cm air gap between the wood wall and the glass, combined with a 10 cm air gap between the brick and wood walls, represented the most effective design. The study confirmed the TW's ability to improve thermal conditions in buildings within the target climate, achieving moderate energy savings during summer, utilizing sustainable clean energy, and contributing to a healthier, greener environment [53].

Likewise, in the Iraqi climate, Ali et al. [3] investigated the impact of air gap width on TW thermal performance among several parameters at room temperature. They studied a room in an actual building in Kirkuk City equipped with a TW and the necessary measurement instruments for data collection. The findings revealed a modest effect of air gap width on system performance. A smaller air gap, such as 2 cm, reduced heat loss through glazing, thereby increasing room temperature and improving system efficiency. Increasing the air gap from 2 to 10 cm resulted in approximately a 13% increase in heat loss through the glazing.

In the same context, Askari and Jahangir [12] examined the effect of air gap thickness (10–25 cm) and phase change materials (PCMs) on TW performance in a three-story residential building in Tehran. They compared a classic TW with an improved PCM-based version, both featuring a 6 mm glass layer, a 15 cm storage wall, and four vents with a total area of 0.16 m². The results showed that a 20 cm air gap was optimal, reducing annual energy consumption by 34% for the classic wall and by 39% for the PCM-enhanced wall during winter.

5.4 Glass layer specifications

The glass layer is one of the key parameters in the TW design phase, as the properties of the outer glass layer affect the reflection or absorption of solar radiation, as well as the heat loss between the external environment and the air gap. The choice of glass layers in a TW depends on the local climate and the orientation of the wall [54]. Generally, TWs are covered with either a single or double glass layer [49]. However, Othman and Zaid [55] reported that double glazing significantly enhances TW performance. Moreover, increasing the thermal resistance of the glass further improves the TW's effectiveness for winter heating due to its ability to reduce heat loss.

Pourghorban and Asoodeh [56] studied the effects of TW orientation and advanced glass systems on comfort, heating, cooling, and overheating durations throughout the year. The researchers conducted theoretical simulations to assess different TW configurations combined with advanced glazing components across various orientations. The models considered the structural and spectral properties of the glazing systems.

The results showed that both orientation and configuration significantly affect overheating periods. Orientation influenced overheating time by 27.5%, while configuration had a 24.7% impact. The effects on heating and cooling periods were smaller, 16.7% and 2.8%, respectively. The most effective results came from south-facing orientations (340°, 350°, 0°, 10°, and 20°), which reduced both heating and overheating times while improving comfort [56].

A study conducted in a typical test room in Izmir, Turkey, by Koyunbaba and Yilmaz [57] evaluated the energy performance of three different types of glass used in TWs: (1) single-layer glass, (2) double-layer glazing, and (3) semi-transparent integrated amorphous silicon (a-Si) photovoltaic modules. The results showed that using double-layer glass provided better insulation during the night. However, single-layer glass resulted in greater heat gain during the day due to higher solar radiation transmission to the storage wall. Therefore, combining single-layer glass with a night-time shutter is recommended to preserve heat gain in winter. In contrast, solar transmittance was lower when using photovoltaic modules. Double glazing with a 25 mm air space also increased the airflow rate, and enhancing the thermal resistance of the glass was found to be more beneficial, as it reduced heat loss through the glass during winter heating.

Oukmi et al. [40] studied a ventilated TW with multi-fold glass in Ifrane, Morocco. Compared to the classic wall, this design reduced energy consumption by 56%, including 95% for heating, and 29% for cooling. The configuration featured a 30 cm-thick storage wall covered by 3 cm of insulation, four glass panels 0.4 m wide, and an air gap 0.35 m wide. The study highlights the potential for constructing high-energy-performance buildings across various climates.

5.5 TW vents

Research has suggested that openings in Trombe storage walls play a key role in reducing temperature fluctuations, improving the efficiency of both cooling and heating, and thereby providing more comfortable indoor conditions for occupants [13, 42, 45]. Vents are especially important for summer cooling, as they help lower indoor temperatures and enhance ventilation. In winter, vents support heating by improving the flow of warm air into the space [36], as shown in Figure 3. To manage indoor temperature fluctuations more effectively, Koyunbaba and Yilmaz [57] proposed the use of an automated operating system to control the timing of vent openings and closures in a TW system.

However, in some cases, TWs lack ventilation openings. A practical and theoretical study examined heat storage within the TW and the temperature distribution inside both the wall and the room. The researchers concluded that the thermal storage of the storage wall reached its peak at 1:00 p.m. in Baghdad in December 2009. Consequently, the thermal distribution within the room was most favorable at that time. Furthermore, the study confirmed that concrete is suitable for thermal storage due to its high thermal conductivity [58].

Aisya and Hendrarsakti [59] had done some testing on two varieties of tsunami walls in Indonesia, where the weather is hot and humid. The first experiment concerned the wall of the TW with no ventilation for three different wall thicknesses. The second set of experiments used the ventilated TW, which has two ventilation holes in the interior space, each 3.5 × 80 cm in size. In the first experiment, they found that a thickness of 25.4 cm was most appropriate. Hence, this thickness from the first experiment was taken and used for the second experiment, in which a ventilated TW with three lower openings was employed in the concrete wall. The lower set of openings measured 20 × 30 cm, each located 30 cm away from either edge. The upper openings were above the lower openings in the glass layer, with the same dimensions and spacing as those at the bottom. From this perspective, the upper-level openings would function as outlets on the windward side, while the lower-level openings would serve as inlets on the side exposed to the wind. It was concluded that this kind of ventilated TW allowed better disordering of indoor temperature than a non-ventilated TW. Figure 4 illustrates the types of TWs based on the availability of ventilation openings.

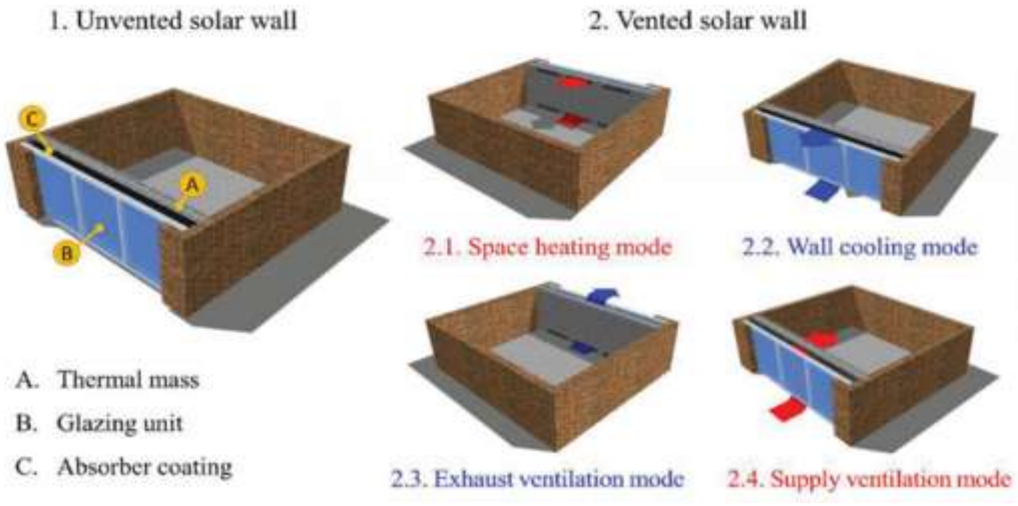


Figure 3. Unvented/ vented TWs basic configurations [60]

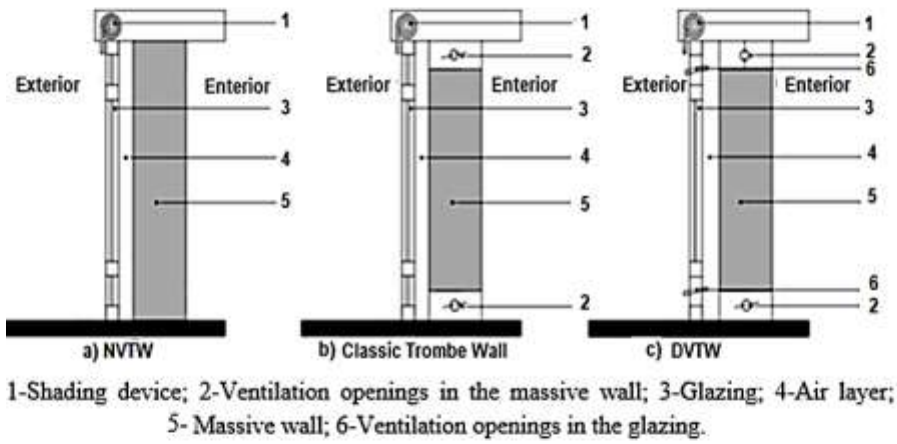


Figure 4. Types of TWs based on the availability of ventilation openings: a) non-ventilated (NVTW); b) Classic or ventilated; c) Double-ventilated (DVTW) [24]

In a hot-dry climate, Elsaid et al. [53] emphasized the importance of vent design in improving the thermal performance of TWs. Six vents, each measuring 28 cm × 40 cm, and various air gap configurations were tested. The research found that vent size and placement significantly affect heat transfer and airflow. The results recommended a 30 cm separation between the wooden wall and the glass panel, and a 10 cm separation between the brick wall and the wooden wall. These findings highlight that well-designed vent configurations enhance passive cooling, contributing to improved thermal comfort and more sustainable energy use.

5.5.1 TW Vents Location

The TW has two primary openings: one at the top and one at the bottom. Hot air enters the room through the upper opening, while cold air is drawn in through the lower opening, creating a continuous air circulation cycle. A gap between the glass and the heating wall allows air to circulate and flow into the space through its upper and lower openings [14, 45, 49]. The roof vents can also be connected to the outside surroundings, as in the idea of solar chimneys, so that they open in summer, and close in winter, thus ventilating and conditioning the building during the summer while ensuring that the airflow is entirely outside the building. In their design of the composite TW [28, 50].

According to Hamidi et al. [25], the efficiency of the TW system in enhancing natural ventilation was evaluated under various Moroccan climate conditions. The researchers used a mathematical model to simulate the wall's effect in a single room across four wall configurations with different vent positions, tested in six regions of Morocco during both summer and winter. The TW used in the study consisted of a 10 cm-thick concrete wall, a 0.5 cm-thick glass cover, and a 10 cm-thick air gap. Four vent setups were tested: "Out-In" with vents at the bottom of the glass and top of the wall, "In-Out" with vents at the bottom of the wall, and top of the glass, "Out-Out" with both vents in the glass, and "In-In" with both vents in the wall. The "In-Out" configuration was most effective in summer, while "In-In" performed best in winter. The study showed that TW is a promising natural ventilation solution, but further research is needed to optimize air gap thickness and glass type for better performance.

Hamidi et al. [17] studied TW as a second façade to support natural ventilation, improve indoor air quality, and thermal comfort. They tested four façade configurations across six Moroccan climates. The TW system covered 1 m² and included a 10 cm concrete wall, 0.5 cm outer glass, a 10 cm air gap, 5 cm expanded polystyrene insulation, and a 10 cm × 20 cm ventilation opening. Results showed the In-In setup, with vents both in the block wall, performed best in winter, while In-Out, with the lower vent in the wall and upper vent in the glass, worked better in summer. Both achieved airflow rates between 200 and 400 m³/hour, improving comfort and lowering energy use. The study recommended further system development and integration with other passive technologies.

5.5.2 Vent shape and number

Ventilation openings vary in shape and size. Kenjo and Najjar [50] designed three TW models with specific dimensions for testing in Lattakia, Syria; one model had two rectangular openings. Chaichan and Abaas [61] tested a TW in winter in Baghdad with ten 1 cm-wide vents for hot air exhaust and ten for cold air intake, improving ventilation and heating through continuous airflow. Moosavi et al. [14] tested a TW on a southern wall in Yazd, Iran, with four rectangular openings—two upper and two lower—which enhanced passive heating, cooling, and ventilation in a dry climate.

Elsaid et al. [53] studied different TW designs to reduce air conditioning in Egypt's hot, dry climate. Their TW system included six rectangular vents. Results showed that vent number and shape are key to ensuring proper air ventilation and circulation.

5.5.3 Vent area

Several studies have investigated the impact of inlet and outlet vent areas on the performance of TWs. Briga-Sá et al. [24] indicated that the recommended vent area, based on literature, is 2% of the TW surface area. The study also noted that multiple small vents perform better than a single large vent. Moosavi et al. [14] examined a bedroom in Yazd City with a TW containing four rectangular vents, each measuring 65 cm × 20 cm, located at the top of the glass, and storage walls. Their findings showed that vent configurations significantly influence the airflow rate through the TW. Appropriate vent size and positioning are essential for enhancing thermal performance and natural ventilation across different seasons.

Fidaros et al. [52] studied the effect of various vent diameters on TW ventilation. Their experiment tested three models from ten ventilated TW configurations, varying the diameters of the upper and lower vents in the storage wall (10, 12.4, and 15 cm). The results indicated that increasing vent diameter improved airflow in the air gap and lowered the outlet air temperature. However, the vent diameter had no significant effect on the overall ventilation performance or airflow pattern in the indoor space.

Kaya et al. [62] evaluated the impact of the vent-to-wall opening area ratio on TW thermal performance in Istanbul. The TW featured a 15 cm-thick concrete storage wall painted black, double glazing, and a 20 cm-wide air gap. The study recommended distributing vents in two rows: lower and upper. The vent area was increased incrementally by 2% per test, beginning with an unventilated wall. Results showed that a TW with eight vents provided effective thermal performance and even heat distribution, with an 8% vent-to-wall ratio. Each vent measured 50 cm × 20 cm, with 25 cm spacing between vents, positioned 15 cm from the top and bottom edges. The findings also indicated that a single large vent, measuring 33.3 cm × 300 cm, and occupying 20% of the wall area, produced the greatest increase in indoor temperature.

Khetib et al. [5] examined the role of vent size in TWs with and without phase change materials (PCMs) in tropical climates during both summer and winter. Three vent widths—17.5 cm, 35 cm, and 70 cm—were tested, each with a height of 20 cm, in a TW with a 15 cm-thick storage wall, and a 5 cm air gap. The results showed that the smallest vent (17.5 cm) enhanced heat transfer and airflow through the TW.

5.5.4 Distance between inlet and outlet, and the outlet inclination angle

Most studies have focused on the typical characteristics of TWs, such as the thickness of the massive wall, the width of the air gap, and the number of glazing layers, often overlooking the role of vents. The study by Fidaros et al. [52] is among the few that examined the impact of vent spacing and inclination angle on TW performance. The results showed that a 2.4 m distance between the upper and lower vents was optimal compared to other tested distances (1.8 m and 2.1 m). Increasing the distance between the inlet and outlet vents significantly enhanced TW efficiency by improving ventilation performance and air distribution, thereby reducing under-ventilated zones. The study also assessed the effect of the upper vent's inclination angle. By adjusting the vent angle by 30 degrees, airflow and ventilation efficiency within the room improved.

Kalair et al. [38] integrated a TW into a nanogrid building and evaluated its energy performance and thermal comfort. The vent spacing was adjusted to 3.5 meters. The findings indicated that appropriate vent spacing optimizes airflow, enhances the thermal performance of the wall, facilitates warm air entry into the room, and improves the air distribution pattern through more even dispersion of heated air.

5.5.5 Vent valves position

When sunlight falls on a TW, it raises the air temperature inside the air gap and decreases air density. As a result, hot air flows upward, creating suction that draws cooler air into the space through the lower opening and allows it to exit through the upper opening, thereby achieving natural ventilation. The position of the valves controls the direction of airflow into and out of the space [8]. Figure 5 illustrates the valve positions in the cross-sectional diagram of the TW.

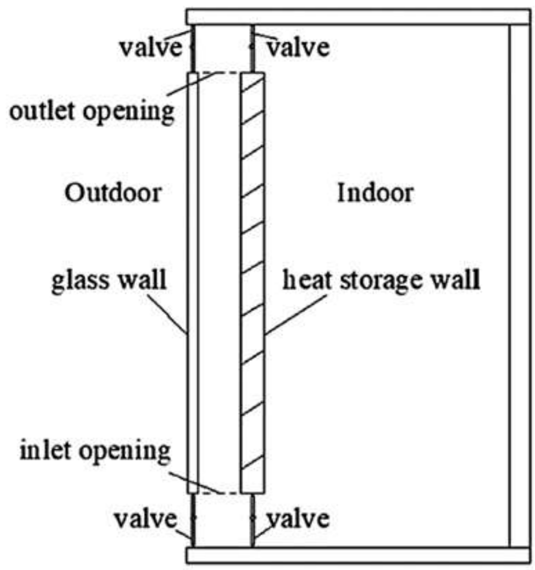


Figure 5. Cross-sectional diagram of the TW [8]

The TW can operate in either heating or ventilation mode by adjusting the valve positions, typically managed by building occupants based on their comfort needs. In summer, the TW functions as a solar chimney, with the upper opening in the storage wall and the lower opening in the glass layer closed. In contrast, during winter, one of the lower openings is closed along with the upper opening in the glass layer [20, 63, 64].

Briga-Sá et al. [24] dealt with vent and valve control and their influences on the thermal performance of TWs. The experimental setup consisted of a double-ventilated TW having four upper vents and four lower ones on both the TW and the glass layer.

The opening and closing of vents are controlled by two types of valves to assess their impact on temperature fluctuations. The results showed that closing the vents without shading devices caused the air layer temperature to rise above 60℃. In contrast, opening the vents while using shading devices reduced thermal contrast and improved the wall's ability to store and gradually release heat during the night, resulting in a thermal difference of up to 9℃ compared to the outside. These findings highlight the role of valves in optimizing heat retention and ventilation in response to temperature variations [24].

5.6 Thermal insulation

Insulating the inner part of the storage wall during both winter and summer improves the performance of the TW. This aspect has been emphasized by researchers, particularly for cooling in summer, where insulation helps prevent excessive heat caused by solar gain through the glass, and subsequent heat transfer to the interior [36, 55]. Thermal insulation also enhances TW performance by allowing the full heat gain of the storage wall to stimulate buoyancy-driven airflow.

Chaichan and Abaas [61] indicated that using phase change materials (PCMs) in the storage wall, such as hydrated salt and paraffin wax, improves the efficiency of TWs. Their study demonstrated the TW's capacity to heat buildings during winter nights in Baghdad. These PCMs are lighter than conventional materials and can store more heat relative to their volume [61].

Similarly, Khalifa and Abbas [65] compared two types of insulation materials used in TWs: one was a paraffin wax wall with a thickness of 50 cm, and the other was a hydrated salt wall coated with PCM with a thickness of 80 cm. Both performed better than a 20 cm-thick concrete wall.

Gupta and Tiwari [41] reported that system performance improved by 56% when thermal insulation was incorporated. Insulating the storage wall addresses the low thermal resistance and night-time heat loss problems associated with classic TWs. Proper insulation also increases the building's ventilation rate when TWs are used.

According to Elsaid et al. [16], insulation layers can significantly reduce the size of the storage wall while increasing its efficiency by up to 56%. Their findings also showed that using thermal insulation can reduce energy dem, and by 32–59% in hot desert regions, 27–50% in continental climates, 29–55% in semiarid climates, 46–73% in Mediterranean climates, and 34–57% in temperate climates.

5.7 Shading devices

Shading devices are an essential component of the TW system, as they significantly influence its thermal performance. Therefore, it is important to regulate their use according to seasonal conditions [66]. One of the main concerns when using TWs in hot-dry climates during the summer months is overheating, which leads to the gradual transfer of unwanted heat into the interior [4, 66]. To prevent this, sliding panels and external shading devices such as roller shutters, overhangs, and venetian blinds should be installed outside the TW during summer [14, 24, 25]. External shading is more effective than internal shading at reducing temperature increases, and can significantly decrease heat gain, thereby improving the thermal performance of the TW and minimizing overheating [66].

In contrast, during winter, shading devices should be placed inside the TW air gap at night to reduce heat loss to the outside when temperatures are low [13, 66]. Several studies have evaluated TW performance in summer. Stazi et al. [64] compared various shading types (brakes, shutters, and solid barriers), ventilation strategies, and insulation levels to assess the thermal behavior of TWs in Mediterranean summer climates. The results indicated that shading, occupancy, and ventilation conditions all affect TW thermal performance in summer.

Jaber and Ajib [23] indicated that the appropriate size of suspended ceilings can shade the Trombe wall when the sun is high in the sky in the summer. In contrast, Trombe wall shading can prevent storage walls from getting hot at times when heat is undesirable. Furthermore, the study highlighted the types of blinds and their location, such as roller blinds to prevent solar rays from entering the building and insulating curtains between the glass and the building walls to prevent heat transfer.

Briga-Sá et al. [13] also found that the darker the shading device, the less solar energy it absorbs, while lighter-colored devices reflect solar energy. TW shading, therefore, prevents the storage wall from overheating when heat is not desirable. The study also examined the effectiveness of different blind types, and their placement, such as roller blinds to block solar radiation, and insulating curtains positioned between the glass and the building wall to reduce heat transfer. Similarly, Chaichan and Abaas [61] incorporated two wooden doors to cover the glass surface of the TW after sunset, demonstrating the use of shading to reduce unwanted heat transmission into the building.

6. OPTIMAL VALUES FOR TW VARIABLES

The optimal values for TW variables can vary depending on specific design goals, climate conditions, and building requirements. However, based on existing research and studies, some general optimal values for key TW variables are presented in Table 2 below. Prozuments et al. [31], in their review study, also identified optimal values for several TW variables. These variables, along with their recommended values based on climatic context, are provided in Table 3 below.

The optimal values of TW variables can be tailored to suit both hot and cold weather conditions. In cold climates, it is essential to minimize heat loss and maximize heat storage. Therefore, thicker walls made from materials with high heat capacity, along with sufficient insulation layers, are necessary. For instance, concrete and stone are preferred due to their high thermal mass, while insulation layers help reduce heat loss during winter nights.

Table 2. Optimal value for TW variables

Elsaid et al. [16]		Xiao et al. [67]		Ibrahim et al. [32]	
Variable	**Value**	**Variable**	**Value**	**Variable**	**Value**
Material	Concrete	Material	Concrete	Material	Concrete or Masonry
Wall Thickness	0.3 to 0.4 meter	Wall Thickness	34 cm for stone, and 32 cm for concrete	Wall Thickness	0.2 to 0.4 meters
Air gap	0.4 to 0.5 meter	Air gap	0.3 to 0.35 meter	Air Gap	0.14 meters
Glazing	Double	Glazing	double or triple-pane, and Low-E double-pane is effective	Glazing	double glazing
Coating Materials	black colour	Coating Materials	low-emissivity (Low-E) coatings	Reflective Surfaces	black or dark, heat-absorbing coating
Ventilation	Position and number of vents are critical factors	Ventilation	8% vent-to-wall-area ratio with multiple vents	Ventilation	at the top and bottom of the wall
Orientation	south-facing orientation	Orientation	south-facing orientation	Orientation	-south-facing in the Northern Hemisphere -north-facing in the Southern Hemisphere
PCM Integration	PCMs with a melting point of 18°C to 30°C	PCM Integration	PCMs with a melting point of 20°C to 30°C	PCM Integration	PCMs with a melting point of 18°C to 30°C
Insulation Material	EPS, Wood, Nano-film	Insulation Material	foam boards, fiberglass, mineral wool. Aerogel is common	Insulation Material	Proper insulation
Insulation Layers thickness	0.2 to 0.4 meters mentioned in different contexts	Insulation Layers thickness	0.32 to 0.34 m	Insulation Layers thickness	

Table 3. Optima value for TW variables based on weather context

Cold Weather		Hot Weather	
Variable	**Value**	**Variable**	**Value**
Material	Concrete or masonry	Material	Concrete or masonry
Thermal Storage Wall Material	Incorporation of PCMs with a melting point of 18°C to 30°C	Thermal Storage Wall Material	Incorporation of PCMs with a melting point of 26°C to 30°C
Air Gap	2 cm to 10 cm	Air Gap	2 cm to 10 cm
Glazing Material	Double or triple with low U-value	Glazing Material	-Use of reflective or low-emissivity coatings -High-transmission glazing with low U-value
Wall Orientation	South-facing walls in the Northern Hemisphere	Wall Orientation	East or west-facing walls
Shading Coefficient	Lower values, 0.2 to 0.5	Shading Coefficient	Higher values, 0.5 to 0.7
Solar Heat Gain Coefficient	Higher values, 0.5 to 0.7	Solar Heat Gain Coefficient	Lower values, 0.2 to 0.5
Ventilation	Properly designed vents	Ventilation	Properly designed vents and using
Wall Surface Treatment	Dark-colored surfaces	Wall Surface Treatment	Light-colored or reflective surfaces
Insulation	Proper insulation of the thermal storage wall	Insulation	Proper insulation of the thermal storage wall
Integration with Other Systems	- Integration with PV/BIPV elements to generate electricity - Use of solar chimneys to improve natural ventilation, and reduce cooling loads	Integration with Other Systems	-Integration with PV/BIPV elements to generate electricity - Use of solar chimneys to improve natural ventilation, and reduce cooling loads

In hot climates, by contrast, the focus is on preventing overheating and maintaining cooler indoor conditions. This requires the use of shading devices, improved ventilation, and materials that dissipate heat effectively. Phase change materials (PCMs) and water-based TWs can enhance indoor comfort by absorbing and releasing heat as needed. Additionally, adjustable blinds and smart control systems allow for real-time temperature regulation, supporting efficient energy use and maintaining a comfortable environment.

Overall, TW parameters can be adjusted to ensure energy efficiency and indoor comfort, depending on specific climatic conditions.

6.1 Costs and practical challenges in real-world implementation of TW systems

Although TWs offer an environmentally friendly and cost-effective solution for passive heating, several logistical and financial challenges often limit their widespread adoption in real-world construction [68].

6.1.1 The initial cost of construction

When compared to conventional wall assemblies, the initial cost of installing TWs is often significantly higher, especially when ventilation systems, double or triple glazing, and thermal mass materials like masonry or PCM-infused panels are included.

The cost increases further when smart control systems, such as sensors, actuators, and automation controllers, are included due to the need for specialized installation and advanced technology. The comparative operational (energy) costs with and without TW are summarized in Table 4.

6.1.2 Practical challenges (Including real-world case studies)

A TW system installed in a residential unit in Sinai, Egypt, is examined in the study "An Urban Living Lab Monitoring, and Post-Occupancy Evaluation for a TW Proof of Concept." The study evaluates the TW's effectiveness as a passive heating and cooling system in a hot, dry region, focusing on sustainable design principles and community involvement [69].

Table 4. Operational (energy) costs for applying TW

Performance Measurement	With TW	Without TW
Energy use for cooling (summer)	A little higher if not adequately ventilated	In tropical environments, it could be lower
Energy use for heating (winter)	20–40% less (cold/temperate zones)	Standard or superior
Capacity needed for HVAC systems	Possibly reduced in size	Standard
Payback period	Depending on energy savings, 5 to 15 years	—
Maintenance	Moderate to low (dust/vent cleaning)	Low
Total energy savings (annual)	Depending on the climate and geography	—

Methodology and implementation. The TW system was designed, built, and operated by locals through a participatory action research approach. The methodological stages that correlate to the project's five primary phases are shown in Figure 6. To ensure affordability and reproducibility, the wall was constructed using locally available materials, including stone, wood, and wool insulation. The key design features included:

- A dark-painted thermal mass wall to absorb solar radiation.
- Double-glazed windows to reduce heat loss
- Movable vents to enable natural ventilation
- Roll-up wool curtains for added insulation
- External wooden shutters to limit solar heat gain.

The system's performance was monitored for one year on a bedroom's southern façade. Data loggers recorded hourly indoor and outdoor temperatures and humidity levels. Post-occupancy evaluations (POEs) used occupant surveys to assess thermal comfort and user satisfaction.

- **Thermal Performance**: Compared to a control room without TW technology, the TW significantly improved indoor thermal comfort by reducing temperature fluctuations and maintaining more stable indoor conditions.
- **Energy Efficiency:** Reducing reliance on traditional heating and cooling methods, the passive design lowered carbon emissions and saved energy.
- **Occupant Satisfaction:** Residents were satisfied with the system's performance and reported improved comfort. Their involvement in construction fostered pride and a better understanding of how the system works.

Community Involvement: By giving locals the tools to preserve and duplicate the system, the participatory method empowered them.

Contextual Design: Making use of regional resources and customary building methods guaranteed that the system was both economically viable and suitable for the local culture.

Comprehensive Evaluation: A comprehensive evaluation of the system's performance was provided by the integration of qualitative input from POEs and quantitative data from environmental monitoring (Figures 7-10).

Limitations and considerations.

- **Manual Operation:** The system required manual adjustments, like opening and closing shutters and vents. Not all users may do this consistently, which can affect performance.
- **Scalability:** The system works well in single-room applications. However, more research is needed to assess its effectiveness and scalability in larger or multi-room homes.
- **Long-Term Durability:** The study lasted only one year. Longer observation would provide insights into the system's maintenance needs and long-term durability.

TW systems offer low-tech, eco-friendly solutions to improve thermal comfort in hot, dry climates. This study highlights the value of community involvement, local materials, and comprehensive evaluation in applying passive solar design in practice.

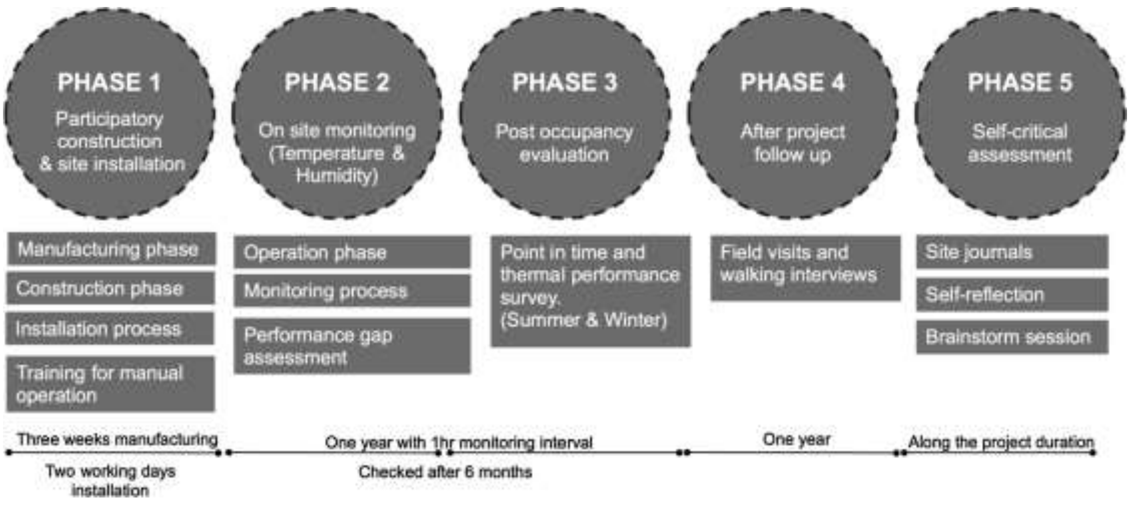


Figure 6. Methodological stages that correlate to the timeline for the project's five primary phases [69]

Figure 7. Delivery of the TW components to the location, and the beginning of the gathering with participation from the locals [69]

Figure 8. The entire TW installation procedure, from cutting the vents to installing the wall's components [69]

Figure 9. Installing the TW components and securing the operational mechanism [69]

Future research should focus on automation to reduce user dependency, test performance across various climates, and assess long-term sustainability.

6.1.3 Practical examples and experimental data (Including simulations to test the validity)

This section includes three real-world studies that are supported by experimental data, real-world examples, and a review of the literature. Using simulations to verify and test the study.

Trombe wall systems are recognized for improving passive solar heating and cooling in buildings. They offer energy-efficient, climate-responsive solutions. While theoretical models and simulations help understand performance, experimental data and real-world case studies are essential. They validate findings and make the results more applicable in practice.

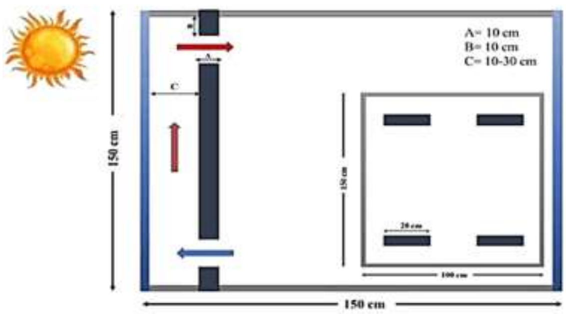
TW systems have become a key passive solar design technique for improving indoor thermal comfort and lowering building energy usage. Through a thermal mass wall positioned behind windows, these systems use solar radiation to heat the interior of buildings. They frequently include an air gap to promote natural convection. Design aspects like air gap geometry, material attributes, and climate have a significant impact on how effective such systems are.

As shown in Table 5, the study "Effect of Air Gap Depth on TW System Using Computational Fluid Dynamics" used CFD simulations to assess how changes in air gap depth influence airflow and heat transfer. To validate the reported thermal behavior, experimental testing on actual walls or physical prototypes under varying environmental conditions is recommended.

In parallel, "CFD Analysis of the Impact of Air Gap Width on TW Performance" provides detailed numerical data on how gap width impacts thermal efficiency. While simulation allows precise control of parameters, field tests or monitored case studies are essential. These would confirm whether theoretical gains in energy efficiency and comfort translate into real-world outcomes. See Table 6 for supporting data.

Figure 10. Teaching locals how to use the TW mechanism while opening and shutting the shutters and wool curtain [69]

Table 5. Using computational fluid dynamics to examine the literature on the impact of air gap depth on TW system

Effect of Air Gap Depth on TW System Using Computational Fluid Dynamics [51]	
The study analyzes how air gap depth, the distance between the glass and the thermal mass in a TW, affects thermal performance using CFD models. It focuses on natural convection patterns, airflow rate, and indoor heat gain.	 **The structure of the conventional TW**
Methodology	A TW's 2D CFD model was created with ANSYS Fluent. The following three air gap depths were assessed: 10 cm, 20 cm, and 30 cm. Simulations were used to represent a steady-state winter daylight scenario. The following parameters were examined: convective heat transfer, air velocity in the air gap, and temperature distribution.

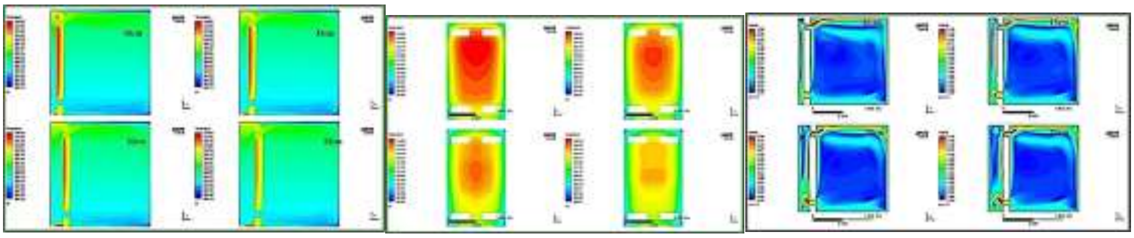
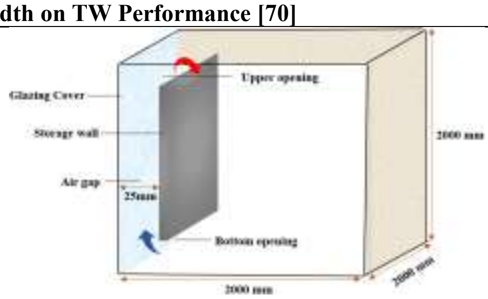
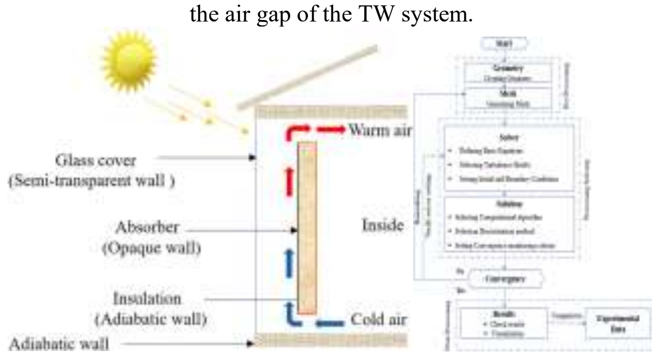
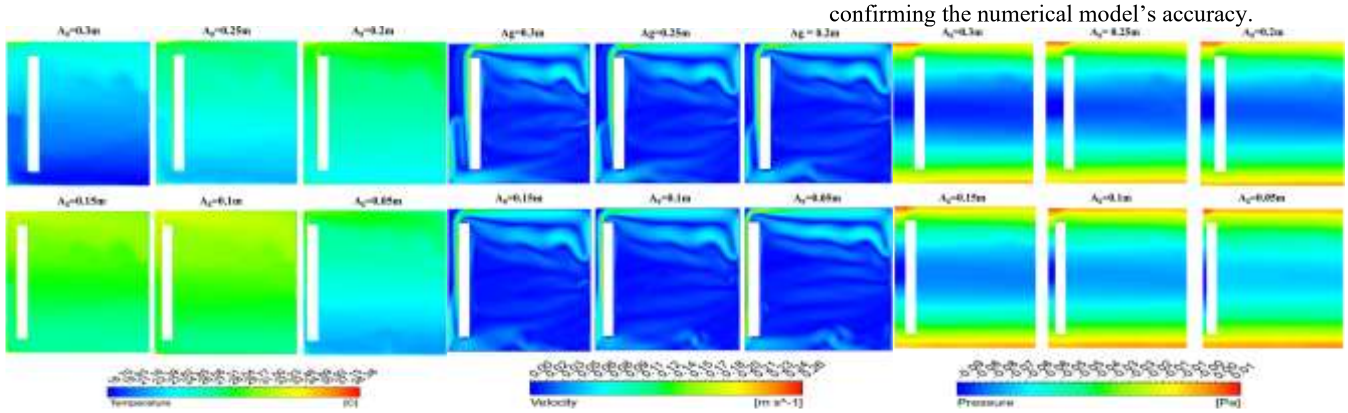
	 **The 3D design of the model**
Key Findings	**Airflow, and Heat Transfer:** • Compared to greater gaps, the 10 cm air gap resulted in higher air velocities, and stronger natural convection. • As a result, the room's convective heat transmission from the TW improved. **Thermal Efficiency:** • Because of reduced thermal stratification, and increased buoyant forces, a 10 cm air gap enhanced thermal performance. **Larger Gaps:** • 20 cm, and 30 cm gaps showed slower airflow, and less effective heat distribution because of poorer convection, although allowing larger air volume.
	
Critical Evaluation	A validated CFD technique offers comprehensive numerical, and visual insights into the behavior of airflow. Demonstrates the significant impact that a modest design parameter (air gap) may have on energy performance. Supports design optimization in passive solar heating systems.

Table 6. CFD analysis of the effect of air gap width on TW performance is the title of the literature review

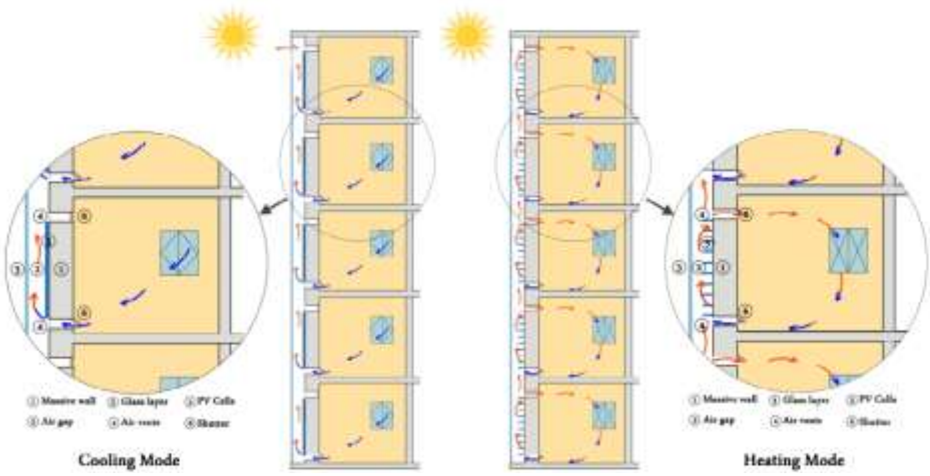
CFD Analysis of the Impact of Air Gap Width on TW Performance [70]	
This study utilizes Computational Fluid Dynamics (CFD) to analyze how varying the air gap width in a TW affects its thermal performance. The simulations aim to predict mass flow rate, temperature fields, and velocity fields under steady conditions.	 **The structure of the conventional TW**
Methodology	The researchers used the k-ε turbulence model and the Discrete Ordinates (DO) radiation model in their CFD simulations. They conducted grid independence tests and analyzed the system under steady-state conditions to ensure reliable and consistent results. 2D CFD simulations using ANSYS Fluent to analyze natural convection in the air gap of the TW system. 

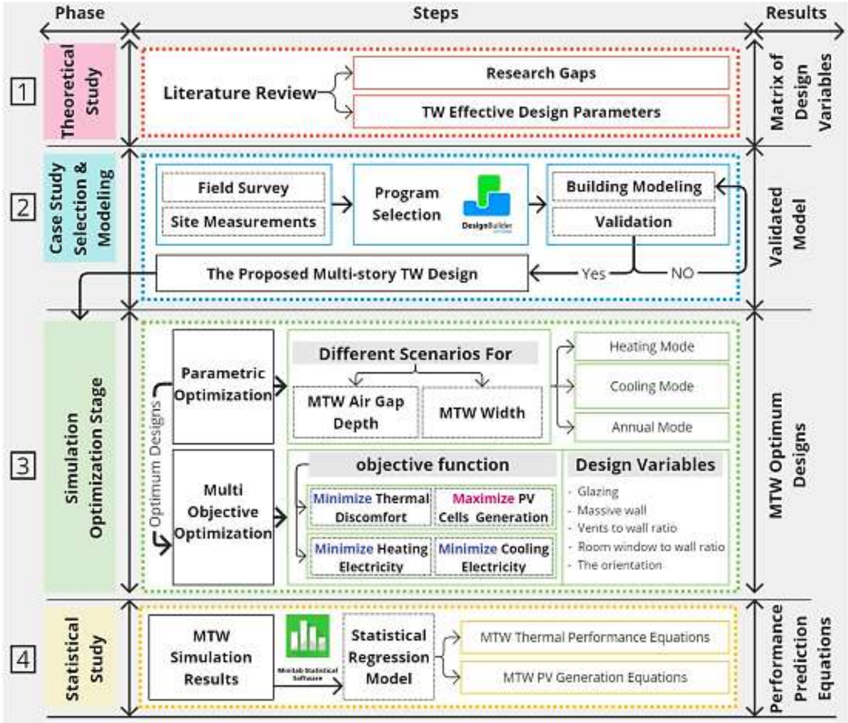
Key Findings	• CFD simulations in 2D with ANSYS Fluent examined natural convection in the TW air gap. • The Discrete Ordinates (DO) radiation model combined with the k-ε turbulence model simulated airflow and solar radiation. • A parametric study tested varying air gap sizes to assess impacts on temperature and velocity profiles. • Thermal performance was evaluated through steady-state simulations under specific boundary conditions. • Optimal Air Gap Width: 0.1 meters (10 cm) delivered the best thermal performance, reaching a maximum air gap temperature near 30°C with effective heat transfer. • Airflow Dynamics: Narrower gaps enhanced natural convection, raising air velocities and improving convective heat transfer to the interior. • Thermal Stratification: Wider gaps reduced heating efficiency due to slower airflow and increased stratification. • Model Validation: CFD results matched existing literature, confirming the numerical model's accuracy.



Critical Evaluation	Comprehensive Analysis: The study thoroughly analyzes the link between air gap width and TW performance, offering key insights for improving passive solar heating. Robust Methodology: The use of validated CFD models and extensive grid independence tests increases result reliability. Practical Implications: Identifying the optimal air gap width helps design more efficient TW systems, promoting sustainable building practices

Table 7. A study of the literature titled "A novel multi-story TW as a passive cooling and heating method in hot climate areas: a simulation-optimization exploration"

An Innovative Multi-Story TW as a Passive Cooling and Heating Technique in Hot Climate Regions: A Simulation-Optimization Study [71]	
This study assesses the thermal performance of a new multi-story TW design for hot climates. It focuses on optimizing the wall configuration to improve passive cooling in summer and heating in winter. The goal is to increase energy efficiency in residential buildings.	 **The proposed MTW heating and cooling mode**
Methodology	Simulation Tools: Researchers used Computational Fluid Dynamics (CFD) simulations with ANSYS Fluent to study the TW system's thermal behavior. Design parameters: Tests examined how different wall materials, glass types, and air gap lengths affected thermal performance. Boundary settings: Simulations ran under steady-state conditions to assess wall efficiency in both cooling and heating modes typical of hot climates.



Key Findings	• The ideal air gap width that maximizes heat transfer by balancing thermal resistance and natural convection is 0.1 meters. • Thermal Performance: The improved TW design reduced reliance on mechanical heating and cooling, resulting in notable gains in indoor thermal comfort. • Energy Efficiency: The study shows that space cooling energy use dropped significantly, highlighting the wall's potential for sustainable building design in hot climates.
Critical Evaluation	Comprehensive Analysis: The study offers architects and engineers a thorough assessment of various design options. Practical Relevance: The study addresses a pressing demand for energy-efficient building solutions in hot climates by focusing on these regions. Optimization Approach: Simulation-optimization techniques ensure the suggested design configurations are both practical, and efficient.

"An Innovative Multi-Story TW as a Passive Cooling and Heating Technique in Hot Climate Regions," the third paper in Table 7, proposes a new Trombe wall design for high-rise buildings in hot climates. While its simulation-optimization framework shows promising results, real-world testing through pilot projects or scaled prototypes is needed to confirm its dual function as a heating and cooling system. These tests should address material performance, air circulation, and occupant comfort.

Together, these studies highlight the theoretical and computational potential of Trombe wall systems. But to bridge the gap between simulation and real performance, integration with experimental data is essential. Future research should focus on hybrid methods that combine CFD modeling with field validation and real-life case studies to support the development of adaptable, climate-resilient buildings.

7. DISCUSSION

TW design, ability, and functioning in sustainable building solutions have been extensively researched. TWs might offer natural ventilation, cooling, and heating; hence, this saves on energy consumption. Detailed studies on different types of TWs and their design parameters such as materials, height, ventilation openings, and air gap depth shall help optimize their performance for different climatic situations. In their advantages, there is a problem of overheating in hotter climates, difficulty in applying innovative types of design, choice of materials for storage walls, and good thermal insulation requirements for TWs. However, optimal design parameter values only serve as guidelines and might need to be overridden concerning a particular building type and its requirements at the local level. But the problem is these issues difficult to address without case studies from actual projects, and experimental proof. Further material investigation, experimentation, and innovative solution engineering are required to build adaptive strategies that maximize TW efficiency and usability. This research emphasizes the potentials of TWs for sustainable and green solutions in building design, while further research and development are essential.

7.1 Tropical climates (hot and humid)

In tropical regions, maintaining cool indoor conditions and avoiding overheating are key challenges, especially during the day and evening when temperatures stay high.

High humidity also reduces the effectiveness of passive evaporative cooling, as shown in Table 8.

7.2 Cold climates

In cold areas, buildings face low solar gain in winter, long heating seasons, and high heat loss through the envelope.

Table 8. Guidelines for design for tropical climates (hot and humid)

Design Feature	Description
Ventilated TWs	Use movable upper and lower vents to enhance natural airflow and promote stack ventilation. Allow cooler night air to dissipate the heat stored during the day. This is key for effective night ventilation.
Devices for Shading	Add vertical fins or horizontal overhangs to block direct sunlight during midday hours. Consider using movable louvers that adjust to the sun's angle.
Light-colored /reflective surfaces	Apply reflective coatings or light-colored wall finishes to reduce heat absorption. Use low-solar-gain glazing to reduce infrared heat transmission.
Reduced Thermal Mass	To avoid storing too much heat that could radiate indoors at night, use lighter materials or thin thermal mass walls.
Selective Glazing or Double Glazing	Use double glazing with low-emissivity (Low-E) coatings to allow visible light inside while reducing infrared heat gain.
Wall Orientation	Position the TW to the south in the Northern Hemisphere or to the north in the Southern Hemisphere. Ensure it gets proper shade during morning and afternoon sunlight.
Combined Landscape Design	Use green buffers like trees and bushes to reduce surface temperatures and increase shade around buildings.

Table 9. Guidelines for design for cold climates

Design Feature	Description
Increased Thermal Mass	In order to gather and preserve solar heat during the day, and release it at night, use thick masonry or concrete walls (≥ 40–45 cm) with a high heat capacity.
Double or Triple Glazing	Double glazing with a 25 mm air gap can improve insulation and minimize heat loss. To improve thermal resistance in particularly cold climates, triple glazing or low-emissivity (Low-E) glass is advised.
Air-Tight Construction	To block cold air infiltration, design the TW system as sealed or semi-sealed without vents. For controlled airflow, use insulated damper systems where vents exist.
Insulated Movable Night Shutters	To prevent reverse heat loss from the Trombe wall to the outside after sunset, use shutters or insulation panels at night.
Selective Coatings on Absorber Surface	To optimize solar absorption and reduce heat reradiation, apply solar-selective coatings like black nickel or chrome to the absorber.
Optimal Wall Orientation, and Angle	For optimal winter solar exposure, orient the wall due south in the Northern Hemisphere. To align the glazing more directly with winter sun angles, consider tilting it slightly if it cannot be vertical.
Narrower Air Gap	To minimize heat loss and encourage convective heat transfer without stratification, use small air gaps of about 10 to 15 cm.

TWs must focus on minimizing heat loss while maximizing heat absorption and storage.

See Table 9 for specific design recommendations.

8. CONCLUSION

TWs represent a significant advancement in passive solar design, offering eco-friendly solutions for cooling, heating, and natural ventilation in buildings. Their performance can be enhanced through careful consideration and optimization of various design parameters, including storage wall thickness, shape, height, area, materials, color, ventilation vents, shading devices, air gap depth, thermal insulation, and glass layer specifications. This review highlights the potential of TWs to reduce energy consumption, improve thermal comfort, and enhance indoor air quality, establishing them as a vital element of green buildings. Further research is needed to strengthen these benefits, explore innovative materials and designs to maximize the efficiency and applicability of TWs across diverse climate conditions.

Table 10. Summary of the literature review

Study	Key Results
Study 1 [51]	This study shows air gap depth is crucial for TW thermal performance. CFD analysis found a 10 cm air gap creates the strongest natural convection, boosting airflow and heat transfer into the interior. Wider air gaps (20 cm and 30 cm), reduced performance due to weaker buoyancy forces, and slower airflow. This shows the need to optimize air gap size to improve energy efficiency in passive solar heating, especially in cold climates.
Study 2 [70]	The paper "CFD Analysis of the Impact of Air Gap Width on TW Performance" shows that air gap width strongly affects the thermal efficiency of a TW system". A 0.1 m gap was found to be optimal for improving heat transfer to the interior, maximizing natural convection, and enhancing airflow. Wider gaps reduced efficiency due to increased stratification and poorer airflow. The study supports using CFD as a method to optimize passive solar heating in Trombe wall design. The study supports using CFD as an effective tool for optimizing passive solar heating in TW design.
Study 3 [71]	This study presents a structured simulation-optimization method to enhance multi-story TW design for hot climates. By identifying optimal designs, especially air gap width, the study supports passive construction methods that boost energy efficiency and thermal comfort. However, experimental validation and transient simulations are needed in future research to fully unlock these systems' potential in real-world settings.

The three studies show TW performance depends heavily on air gap size, design, and climate. CFD simulations help identify the best air gap for heat transfer and airflow. Modern multi-story TWs with smart controls provide adaptive solutions for passive heating and cooling in hot or variable climates. To maximize efficiency and comfort, gap size, materials, and ventilation must be carefully selected, as detailed in Table 10.

9. RECOMMENDATION

In order to greatly improve the flexibility and thermal performance of TW systems in contemporary structures, it is highly advised that:

- Integrate Control Systems with Smart: For optimum energy efficiency, use IoT-based sensors and AI-driven logic to dynamically modify shading devices, venting, and even thermal mass activation.
- As an illustration, smart vents can automatically close at night to preserve heat, and open on bright winter days to let warm air in.
- Employ automatic actuators to regulate the top and lower vents in response to occupancy, solar radiation, and current indoor and outdoor temperatures.

Smart design for climate: Smart insulation shutters can close automatically at night in cold climates to reduce heat loss.

In tropical regions, effective shading and ventilation enhance nighttime cooling and help prevent overheating.

Integrate with advanced materials: Combining phase change materials (PCMs), electrochromic glass, and thermal insulation shutters that respond to control inputs enhances smart system effectiveness.

Integrating intelligent, responsive technology into TW architecture creates a useful transition from passive to hybrid systems. This boosts flexibility, performance, and user control. Further research in this area will keep TWs relevant in high-performance, sustainable design.

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